Nuclear modification factor of non-photonic electrons in heavy-ion collisions and the heavy-flavor baryon to meson ratio

Yongseok Oh* and Che Ming Ko†
Cyclotron Institute and Physics Department, Texas A&M University, College Station, Texas 77843, U.S.A.

(Dated: June 16, 2009)

The nuclear modification factor R_{AA} of non-photonic electrons in Au + Au collisions at $\sqrt{s_{NN}} =$ 200 GeV is studied by considering the decays of heavy-flavor hadrons produced in a quark coalescence model. Although an enhanced Λ_c/D^0 ratio is predicted by the coalescence model, it is peaked at small transverse momenta (~ 2 GeV) due to the large difference between heavy and light quark masses. As a result, the enhanced Λ_c/D^0 ratio, which is expected to suppress the electron R_{AA} as the branching ratio of Λ_c decay into electrons is smaller than that of D^0, does not lead to additional suppression of the electron R_{AA} at large transverse momenta (≥ 5 GeV), where the suppression is mainly due to heavy quark energy loss in produced quark-gluon plasma. Also, the enhanced $\Lambda_b/\bar{B}^0$ ratio predicted by the coalescence model has even smaller effect on the non-photonic electron R_{AA} as bottom baryons and mesons have similar branching ratios for semi-leptonic decays into electrons.

PACS numbers: 25.75.-q, 25.75.Cj, 25.75.Dw

Heavy-flavor hadrons are useful for probing the properties of the dense matter produced in relativistic heavy-ion collisions. Although D mesons were measured in d + Au collisions at the Relativistic Heavy Ion Collider (RHIC) [1], there is not yet direct measurement of open charm or open bottom hadrons in heavy-ion collisions. Instead, heavy-flavor hadron production in heavy ion collisions was studied through measurements of non-photonic electrons from their decays [2]. The transverse momentum (p_T) spectrum of these electrons in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV were measured for several centralities by the PHENIX Collaboration [3]. The resulting nuclear modification factor R_{AA}, defined by the ratio of the p_T spectrum of non-photonic electrons in heavy ion collisions dN^e_{AA}/dp_T to that from proton-proton collisions dN^e_{pp}/dp_T multiplied by the initial number of NN binary collisions $\langle N^{AA}_{\rm coll}\rangle$, i.e.,

$$R_{AA} = \frac{dN^e_{AA}/dp_T}{\langle N^{AA}_{\rm coll}\rangle\, dN^e_{pp}/dp_T}, \tag{1}$$

shows that the production of heavy-flavor hadrons in heavy-ion collisions is suppressed as much as that of pions. This has raised a challenging question on heavy quark interactions in medium as perturbative Quantum Chromodynamics (pQCD) predicts that heavy quarks lose less energy in the quark-gluon plasma than gluons and light quarks, which is responsible for the observed large suppression of high p_T pions. Various ideas have been suggested to explain the observed small non-photonic electron R_{AA}, and these include the introduction of very large medium opacity [4], two-body [5, 6, 7] and three-body collisional energy loss [8], and the collisional dissociation of heavy mesons in medium [9]. It is also proposed that an enhancement of the Λ_c/D^0 ratio would reduce the R_{AA} of non-photonic electrons [10, 11]. This is based on the observation that the branching ratio for $\Lambda_c \to e$ decay is smaller than that for $D^0 \to e$ decay. Therefore, if the Λ_c/D^0 ratio is enhanced as in the case of p/π and Λ/K^0 ratios, the R_{AA} of non-photonic electrons would be smaller than that only due to heavy quark energy loss. In Ref. [11], it was claimed that this effect may explain about 20% of the suppression of R_{AA}. Since the origin of the Λ_c/D^0 enhancement is unknown, this ratio is assumed in Refs. [10, 11] to have either the same p_T dependence as in the Λ/K data or a Gaussian form.

Recently, the enhancement of Λ_c yield in relativistic heavy ion collisions was suggested as a possible test of the diquark model for the structure of heavy baryons [12, 13]. Estimates based on the quark coalescence model for heavy-flavor hadron production show that the existence of diquarks in both the quark-gluon plasma and the Λ_c would enhance the Λ_c/D^0 ratio by a factor of ten and five, respectively, compared to those of PYTHIA simulation for pp collisions and of a simple thermal model. (See, e.g., Ref. [14] for the quark coalescence model.) Furthermore, it was shown that the enhancement of the Λ_c/D^0 ratio could be better seen at low p_T region where heavy quark fragmentation is less important. Therefore, the enhancement of Λ_c/D^0 ratio is expected to result in the suppression of R_{AA} only at low p_T region. This is in contrast to the assumption of Refs. [10, 11] that the Λ_c/D^0 enhancement continues to the large p_T region. In this report, we calculate the non-photonic electron R_{AA} based on the results from Ref. [13]. We also discuss the contribution from the enhanced $\Lambda_b/\bar{B}^0$ ratio to the non-photonic electron R_{AA}.

For calculating the electron spectrum from heavy hadron decays, information on the branching ratios of semi-leptonic decays of heavy hadrons into electrons is needed. The experimental data complied by the Particle Data Group [15] for the branching ratios of these de-

*Electronic address: yoh@comp.tamu.edu
†Electronic address: ko@comp.tamu.edu

Decay channel	D^0	D^+	D_s^+	Λ_c
BR(e^+ + anything)	$6.53 \pm 0.17\,\%$	$16.0 \pm 0.4\,\%$	$8\,^{+6}_{-5}\,\%$	$4.5 \pm 1.7\,\%$
BR($Ke^+\nu_e$)	$3.58 \pm 0.06\,\%$	$8.6 \pm 0.5\,\%$		
BR($K^*e^+\nu_e$)	$2.18 \pm 0.16\,\%$	$3.66 \pm 0.21\,\%$		
BR($\eta\ell^+\nu_\ell$)			$2.9 \pm 0.6\,\%$	
BR($\eta'\ell^+\nu_\ell$)			$1.02 \pm 0.33\,\%$	
BR($\Lambda e^+\nu_e$)				$2.1 \pm 0.6\,\%$
BR(pe^+ + anything)				$1.8 \pm 0.9\,\%$

TABLE I: Branching ratios of major semi-leptonic charm hadron decays into electrons as listed by the Particle Data Group [15].

cays are, however, ambiguous as shown in Table I. One can estimate the effect of the Λ_c/D^0 enhancement on the electron R_{AA} roughly by considering semi-leptonic decay of heavy hadrons in each channel as in Ref. [11],

$$R_{AA} = \frac{\{n_e(D^0) + n_e(D^+) + n_e(D_s) + n_e(\Lambda_c)\}_{AA}}{\{n_e(D^0) + n_e(D^+) + n_e(D_s) + n_e(\Lambda_c)\}_{pp}}, \tag{2}$$

where $n_e(H)$ is the number of electron produced by the decay of hadron H, and the number of binary collisions is included in the numerator. Since the branching ratio of Λ_c decay into electron is smaller than that of charmed mesons, the enhanced Λ_c/D^0 ratio indeed suppresses the electron R_{AA} if the momentum difference between electrons and the decayed charmed hadrons is neglected. In Ref. [11], it was claimed that if the enhancement factor, $C = (\Lambda_c/D^0)_{AA}/(\Lambda_c/D^0)_{pp}$, is 12, the electron R_{AA} is reduced by about 20%. More quantitative understanding of the effect of enhanced Λ_c/D^0 ratio on the R_{AA} of non-photonic electrons requires, however, a better understanding of the branching ratios of heavy hadron decays, including the decays to four-body final states, as well as the production mechanism of heavy-flavor hadrons in both pp and AA collisions. The latter is addressed in the present study.

We use the coalescence model calculation presented in Ref. [13], which is based on the coalescence formulas

$$\begin{aligned}\frac{dN_B}{d\boldsymbol{p}_B} &= g_B \frac{(2\sqrt{\pi})^6(\sigma_1\sigma_2)^3}{V^2}\int d\boldsymbol{p}_1 d\boldsymbol{p}_2 d\boldsymbol{p}_3 \frac{dN_1}{d\boldsymbol{p}_1}\frac{dN_2}{d\boldsymbol{p}_2}\frac{dN_3}{d\boldsymbol{p}_3} \\ &\quad\times \exp\left(-\boldsymbol{k}_1^2\sigma_1^2 - \boldsymbol{k}_2^2\sigma_2^2\right)\delta(\boldsymbol{p}_B - \boldsymbol{p}_1 - \boldsymbol{p}_2 - \boldsymbol{p}_3),\end{aligned} \tag{3}$$

for baryon production from three-quark coalescence and

$$\begin{aligned}\frac{dN_M}{d\boldsymbol{p}_M} &= g_M \frac{(2\sqrt{\pi}\sigma_{dq})^3}{V}\int d\boldsymbol{p}_1 d\boldsymbol{p}_2 \frac{dN_1}{d\boldsymbol{p}_1}\frac{dN_2}{d\boldsymbol{p}_2} \\ &\quad\times \exp\left(-\boldsymbol{k}^2\sigma_{dq}^2\right)\delta(\boldsymbol{p}_B - \boldsymbol{p}_1 - \boldsymbol{p}_2),\end{aligned} \tag{4}$$

for both baryon and meson production from diquark-quark coalescence and from quark–anti-quark coalescence, respectively. For the details on the model and parameters used in the calculations, we refer to Ref. [13]. For the heavy quark energy loss, we use the parametrization given in Ref. [8],

$$\begin{aligned} L_c &= 0.8\exp(-p/1.2) + 0.6\exp(-p/15), \\ L_b &= 0.36 + 0.84\exp(-p/10), \end{aligned} \tag{5}$$

for charm and bottom quarks, respectively, where p is the transverse momentum in units of GeV. As shown in Ref. [13], compared with charmed hadron production via fragmentation of charm quarks, the yield of D^0 mesons in heavy ion collisions is suppressed in the quark coalescence model as a result of enhanced production of Λ_c. (See the small window in Fig. 1 for the Λ_c/D^0 ratios.) This happens in models based on both the three-quark coalescence and the diquark-quark coalescence. In Fig. 1, we plot the electron spectrum from charm hadron decays for central Au + Au collisions at mid-rapidity ($|y| \leq 0.5$). As a reference, results from the decays of charmed hadrons produced via δ-function fragmentation of charm quarks, i.e., charm quark and produced hadrons have same p_T, without and with energy loss are given by the solid line and dashed line, respectively. These electron spectra include contributions from decays of D^0, D^+, D_s, Λ_c and their anti-particles, as production of electrons from charmed hadrons other than D^0 is not negligible, particularly if there is a large enhancement of the Λ_c/D^0 ratio [10]. Compared with the case that these charmed hadrons are produced from fragmentation of charm quarks via a δ-function fragmentation, coalescence models are seen to give a somewhat suppressed electron spectrum. We note that the uncertainties in the branching ratios as shown in Table I can affect the electron spectrum. More discussions on these uncertainties can be found in Ref. [16].

Our results for the non-photonic electron R_{AA} are presented in Fig. 2. Here, we consider five cases for investigating the role of the enhancement of the Λ_c/D^0 ratio in the electron R_{AA}. First, the solid line is the electron R_{AA} for the case with charm quark energy loss in the δ-function fragmentation approximation as discussed in Ref. [8]. Shown by the dotted line is the result from the coalescence model when *only* D mesons are allowed to be produced. If other charmed hadrons are allowed to be produced, the contribution from the D^0 mesons to the electron spectrum is suppressed and leads to the suppressed electron R_{AA} as can be seen by the dot-dashed line. The dashed and dot-dot-dashed lines are obtained

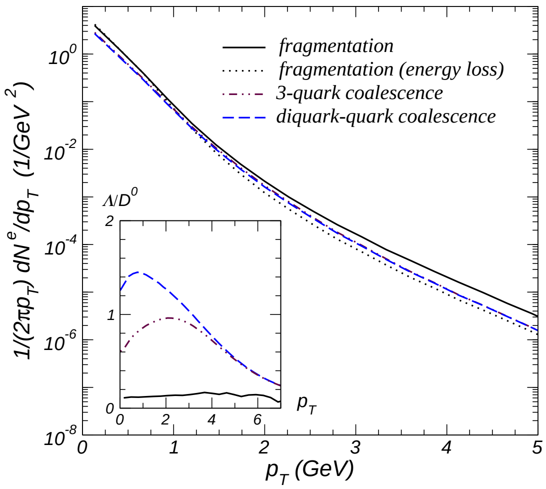

FIG. 1: Spectra of electrons from decays of all charmed hadrons. Shown in the inset are the Λ_c/D^0 ratios in fragmentation and in both the three-quark and diquark-quark coalescence models.

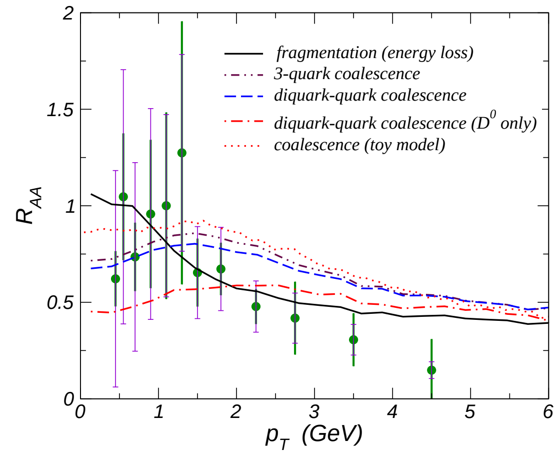

FIG. 2: The electron R_{AA} in the central collision of Au+Au at $\sqrt{s_{NN}} = 200$ GeV from charmed hadrons. The solid line is the result obtained from only fragmentation of heavy quarks with energy loss. The dot-dot-dashed (dashed) line is for the three-quark (diquark-quark) coalescence model, while the dot-dashed line is obtained with D^0 meson only in the diquark-quark coalescence model. The dotted line is from the toy model described in the text and the data are from Ref. [3].

by allowing the decays of all charmed hadrons into electrons in diquark and three-quark coalescence, respectively, and are the main results of this study. Therefore, by comparing the dotted line and the dashed line, one can see that the enhanced Λ_c/D^0 leads to suppression of the electron R_{AA}.

However, when we compare our result for the electron R_{AA} with that of fragmentation with energy loss, the enhancement of the Λ_c/D^0 ratio does not cause the suppression of the electron R_{AA}. This is because the enhancement of Λ_c/D^0 ratio in the coalescence model appears mainly in the region of $p_T \leq 5$ GeV. In addition, we found that the crossover of the coalescence and fragmentation is at $p_T \sim 0.75$ GeV. As a result, the suppression of the R_{AA} for non-photonic electrons appears also at low p_T region ($p_T \leq 3$ GeV). Thus, the calculated R_{AA} underestimates the data [3] at low p_T and overestimates it at large p_T. Including the decay of Λ_c, whose branching ratio of decaying into an electron is not small in comparison to that of D^0, increases the electron R_{AA}. We also found that the difference between the results of the three-quark and the diquark-quark coalescence models is not large. Therefore, in the coalescence model considered here, more quenched charm quark spectrum is needed to explain the small electron R_{AA} observed in experiments.

Our results that the enhancement of Λ_c/D^0 ratio does not cause the suppression of R_{AA} is in sharp contrast with those of Refs. [10, 11]. The reason for this is due to the difference in the Λ_c/D^0 ratio at large p_T region. In both Refs. [10, 11], a constant enhancement factor is assumed for the Λ_c/D^0 ratio at large p_T region. Besides the assumption that the Λ_c/D^0 ratio is the same as the Λ/K_S^0 ratio, it is further assumed in Ref. [10] that $\Lambda_c/D^0 = 0.33$ for large p_T, where no data for Λ/K_S^0 exist. In Ref. [11], an even larger constant enhancement factor $C \simeq 12$ was introduced to the Λ_c/D^0 ratio that was assumed to have a Gaussian shape in p_T. This large enhancement of Λ_c/D^0 at large p_T would then lead to the suppression of R_{AA} at intermediate and large p_T (≥ 5 GeV).

In our case, although the Λ_c/D^0 ratio is enhanced compared to that in pp collisions, the enhancement is mainly at small p_T and the Λ_c/D^0 ratio remains comparable to that of pp collisions at large p_T ($> 7 \sim 8$ GeV) region. Therefore, the effect of the Λ_c/D^0 enhancement on the electron R_{AA} cannot be seen in the intermediate electron p_T region. Furthermore, charmed hadrons produced by coalescence with light quarks have larger values of p_T than that of the charm quark inside a hadron, which results in the shift of charmed hadron p_T spectra to the larger p_T region. Therefore, at large p_T region, we have more charm hadrons than those produced by δ function fragmentation of charm quarks. Although this effect is not large compared to the case for light hadrons, it increases the electron R_{AA}. As a result, we have a larger R_{AA} at intermediate electron p_T compared to that from the fragmentation of quenched heavy quarks.

As the electron p_T increases, electrons from bottom hadron decays become important. The p_T at which electrons from charmed hadron decays and from bottom hadron decays intercepts depends on the model for heavy quark energy loss in the quark-gluon plasma. Since heavy quark energy loss is suppressed as its mass increases [17], this momentum becomes smaller once heavy quark energy loss is included. Therefore, semi-leptonic decays of bottom hadrons should be considered at large electron p_T region, and this would further increase the electron R_{AA}.

The decays of bottom hadrons into electrons are not well-known. There are two processes through which elec-

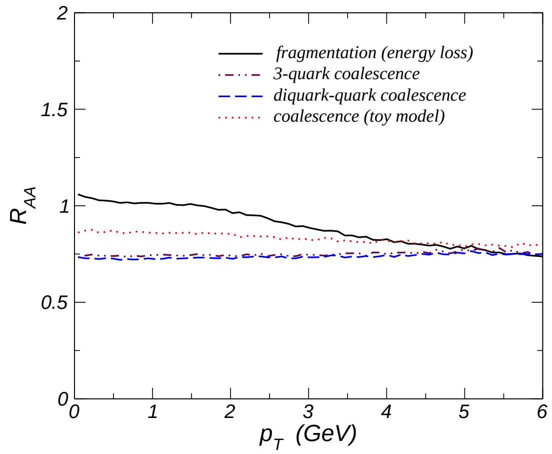

FIG. 3: The electron R_{AA} in the central collision of Au+Au at $\sqrt{s_{NN}}$ = 200 GeV from bottom hadrons. Notations are the same as in Fig. 2.

trons are produced from bottom hadron decays. One is the direct production of electrons from bottom hadron decays, such as $B \to e\nu_e X_c$, where X_c denotes any charm meson. The produced X_c can again decay into electrons. Therefore, bottom hadrons produce primary and secondary electrons. In addition, for vector mesons, B^* and B_s^*, they first decay into $B\gamma$ and $B_s\gamma$, respectively, and electrons are then produced from the decay of resulting pseudoscalar mesons. Currently available experimental data show that the branching ratios of bottom hadrons decaying into electrons are nearly independent of the light quark content of bottom hadrons [15],

$$\begin{aligned} \mathrm{BR}(B^\pm \to e^+\nu_e X_c) &= 10.8 \pm 0.4\,\%, \\ \mathrm{BR}(B^0 \to e^+\nu_e X_c) &= 10.1 \pm 0.4\,\%, \\ \mathrm{BR}(B_s \to \ell^+\nu_e D_s + \text{ anything}) &= 7.9 \pm 2.4\,\%, \\ \mathrm{BR}(\Lambda_b \to \ell^-\bar{\nu}_e \Lambda_c^+ + \text{ anything}) &= 9.9 \pm 2.6\,\%. \end{aligned} \quad (6)$$

The paucity of experimental data for the branching ratio of each channel in semi-leptonic decays of bottom hadrons makes it difficult to compute the electron spectrum from bottom hadron decays. Nevertheless, one can estimate the effect of $\Lambda_b/\bar{B}^0$ enhancement to the electron R_{AA} in a qualitative way by using the formula given in Eq. (2). In Ref. [13], we have observed a large enhancement of the $\Lambda_b/\bar{B}^0$ ratio in the coalescence model. However, since the branching ratio of $B \to e$ and $\Lambda_b \to e$ are similar, enhancement of Λ_b baryon produces more electrons, which compensates almost the reduced number of electrons from B decays. This can also be verified through Eq. (2). Namely, if we use the branching ratios given in Eq. (6), R_{AA} changes from 1.0 with $C = 0$ to 0.95 with $C \to \infty$. This shows that the effect of the $\Lambda_b/\bar{B}^0$ enhancement on the electron R_{AA} is very small compared to that for charm hadrons. This is shown explicitly in Fig. 3. By considering the large uncertainty in the branching ratio of Λ_b decays, the effects of $\Lambda_b/\bar{B}^0$ enhancement is small, in particular at large p_T region, where the electron R_{AA} is expected to be governed by bottom hadron decays.

Although the multiplicities of multi-heavy-quark baryons are very small, production of heavy baryons containing one heavy quark and one or two strange quarks is not negligible. In the coalescence model of Ref. [13], we found that the sum of the multiplicities of Ξ_Q, Ξ_Q', and Ω_Q is as large as 30 $\sim$ 50% of the multiplicity of Λ_Q, where Q stands for c or b. However, the branching ratios of these hadrons have not been measured and the electron spectrum from the decays of these baryons thus can not be estimated.

In summary, we have studied the transverse momentum spectrum and the nuclear modification factor R_{AA} of non-photonic electrons from heavy hadron decays in relativistic heavy ion collisions. Contrary to the models of Refs. [10, 11], which assume an enhanced Λ_c/D^0 ratio at large p_T region, the large enhancement of Λ_c/D^0 ratio predicted in the coalescence model [13] occurs mainly in the low p_T region and the heavy quark fragmentation remains dominant at large p_T region. As a result, no additional suppression to the electron R_{AA} due to enhanced Λ_c/D^0 ratio is obtained at large p_T region. We have also estimated the role of $\Lambda_b/\bar{B}^0$ enhancement in the electron R_{AA} and found that the enhancement of Λ_b baryon production does not affect the electron R_{AA} produced by bottom hadron decays because of similar branching ratios of bottom meson and Λ_b decays into electrons.

Acknowledgments

This work was supported by the US National Science Foundation under Grants No. PHY-0457265 and PHY-0758115 and by the Welch Foundation under Grant No. A-1358.

[1] STAR Collaboration, J. Adams *et al.*, Phys. Rev. Lett. **94**, 062301 (2005).
[2] PHENIX Collaboration, S. S. Adler *et al.*, Phys. Rev. Lett. **96**, 032001 (2006).
[3] PHENIX Collaboration, A. Adare *et al.*, Phys. Rev. Lett. **98**, 162301 (2007).
[4] N. Armesto *et al.*, Phys. Lett. **B637**, 362 (2006).
[5] M. G. Mustafa, Phys. Rev. C **72**, 014905 (2005).
[6] H. van Hees, V. Greco, and R. Rapp, Phys. Rev. C **73**, 034913 (2006).
[7] B. Zhang, L. W. Chen, and C. M. Ko, Phys. Rev. C **72**, 024906 (2005).
[8] W. Liu and C. M. Ko, J. Phys. G **34**, S775 (2007); nucl-th/0603004; C. M. Ko and W. Liu, Nucl. Phys.

A783, 233c (2007).
[9] A. Adil and I. Vitev, Phys. Lett. **B649**, 139 (2007).
[10] P. Sorensen and X. Dong, Phys. Rev. C **74**, 024902 (2006).
[11] G. Martínez-García, S. Gadrat, and P. Crochet, Phys. Lett. **B663**, 55 (2008), **B666**, 533(E) (2008).
[12] S. H. Lee, K. Ohnishi, S. Yasui,, I. K. Yoo, and C. M. Ko, Phys. Rev. Lett. **100**, 222301 (2008).
[13] Y. Oh, C. M. Ko, S. H. Lee, and S. Yasui, Phys. Rev. C **79**, 044905 (2009).
[14] V. Greco, C. M. Ko, and R. Rapp, Phys. Lett. **B595**, 202 (2004).
[15] Particle Data Group, C. Amsler *et al.*, Phys. Lett. **B667**, 1 (2008), http://pdg.lbl.gov.
[16] P. Sorensen, Eur. Phys. J. C **49**, 379 (2007).
[17] M. Djordjevic, M. Gyulassy, R. Vogt, and S. Wicks, Phys. Lett. **B632**, 81 (2006).